Some Results of a Study of Ultra-Short-Wave Transmission Phenomena *

By C. R. ENGLUND, A. B. CRAWFORD and W. W. MUMFORD

The results of a series of transmission experiments made in the range 3.7 to 4.7 meters and over distances up to 125 miles are reported. These observations were chiefly confined to the region reached by the directly transmitted radiation and are found in good agreement with the assumption that such transmission consists mainly of a directly transmitted radiation plus the reflection components which would be expected from the earth's contour. The residual field not thus explained consists of a more or less pronounced diffraction pattern due to the irregularities of the earth's surface. A hill-to-hill transmission has three demonstrable reflection surfaces.

Quantitative checks on hill-to-hill transmission have been obtained and it has been found that a field intensity of 40 microvolts per meter gives very good transmission. Static is ordinarily entirely absent and no Heaviside layer reflections have been observed.

The almost universal standing wave diffraction patterns have been studied and sample records are given. The methods of measuring field intensity which we have used are described in an appendix. No long range transmissions, such as harmonics of distant (greater than 500 miles) short-wave stations would yield, have been observed.

Introduction

THIS paper details the results of certain studies which have been made on phenomena connected with the transmission of ultra-short waves during the past few years. The work was carried on coincidently with that described in the companion paper by Schelleng, Burrows, and Ferrell.[1] It deals in particular with the establishment of the presence of various ground reflections which must be taken into account in computing ultra-short-wave transmission and with the local disturbances due to both stationary and moving near-by objects.

Apparatus

The transmitting apparatus used by us possessed little novelty; one type of generator has already been described in an earlier paper,[2] a second type consisted of a pair of 75-watt tubes operated "push-pull" and fed by a constant-current modulating system of orthodox type. This latter apparatus served permanently as station W2XM at our Holmdel laboratory, and was ordinarily modulated with the output from a broadcast receiver. We first employed superregenerative re-

* Published in *Proc. I. R. E.*, March, 1933.

[1] Schelleng, Burrows, and Ferrell, "Ultra-short-wave propagation," this issue of *Bell Sys. Tech. Jour.*

[2] *Bell Sys. Tech. Jour.*, vol. 7, p. 404; July (1928).

ceivers and constructed several different types of these. All the quantitative data, however, were obtained with a measuring set employing a double detection receiver.

This receiver is of much the same type as the one described by Friis and Bruce,[3] the modifications in the short-wave circuits necessary to reach the ultra-short-wave range being obvious if not exactly easy to carry out. The intermediate frequency is 1300 kilocycles; there are five amplifier stages preceded by a double tube short-wave detector and followed by a single tube low-frequency detector. The band width (6 decibels down) is approximately 80 kilocycles, and the over-all gain 103 decibels. The amplifier tubes are shielded grid type, and the beating oscillator input is introduced, balanced, in the first detector grid-filament connection. The ultra-short-wave tuning circuits have commercial micrometer heads clamped to the condenser dials. This has proved to be a satisfactory type of vernier adjustment. The shielding extends to the individual tubes and coupling circuits and is complete and thorough. By-pass filters to ground are on all the power input connections. The range is 3.7 to 12 meters using several sets of coils. Two photographs of this receiver are given in Figs. 1a and 1b. For some of this work a manually operated gain recorder was fastened on the set base, with operating pen belted to the set attenuator handle. This recorder is a remodeled sample of the type 289 General Radio fading recorder.

Experimental, Preliminary

The first ultra-short-wave receptions, made in September, 1930, with the superregenerative receiver, showed that a cross-country transit was accompanied by marked variations in field intensity over even rather short distances (one meter for example). Locations were readily found where the reception was very weak, usually areas, as gullies, below the average land level. Hilltop reception was uniformly good and a range of 50 miles (80.5 kilometers) was attained on the third trip. At this site (Musconetcong Mountain, N. J.) the reception, weak at the ground level, was greatly improved by carrying the receiver to the top of an airplane beacon tower. A 75-mile (120.8-kilometer) reception at the Pocono Mountains in Pennsylvania failed, the path being unfavorable for the amount of power available at the transmitter. There was ample indication that straight-line or "optical" transmission was not the only possibility, and there were indications that both earth-reflected and earth-diffracted radiations were present. No fading and no static were noticed. Later trips added little of sig-

[3] *Proc. I. R. E.*, vol. 14, p. 507 (1926).

nificance to these observations as the superregenerative receiver is fundamentally incapable of quantitative field strength indications.

Further work was therefore undertaken using the double detection field strength measuring set. The transmitter site was at first the same

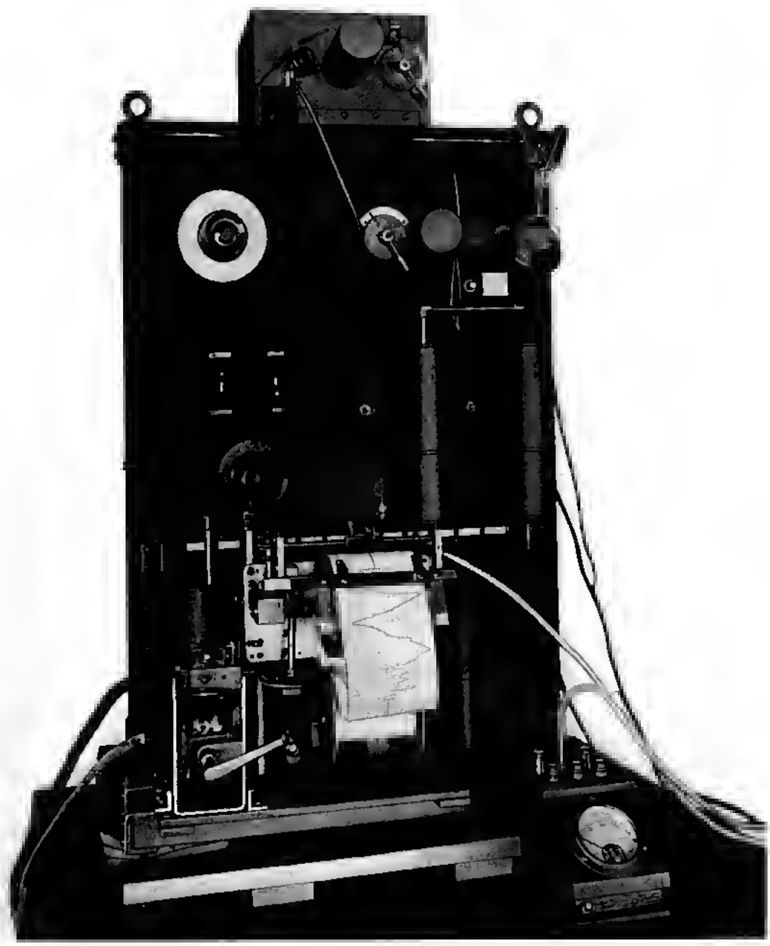

Fig. 1a—Front view of measuring set.

as for the preceding autumn, viz., the Holmdel Laboratory where a half-wave center-tapped antenna on a 65-foot (20-meter) pole was fed with a simple parallel wire transmission line of No. 14 B & S gauge tinned copper wire, 1/4-inch (0.635-centimeter) spacing, with 246 ohms characteristic impedance. With the antenna impedance equal

to approximately 73 ohms the mismatch did not exceed 4 to 1 which gave less than one decibel added loss over impedance matching.[4] As a considerable wave-length range had to be covered, a single wave-length match was of no utility. An open-wire line of less than 250

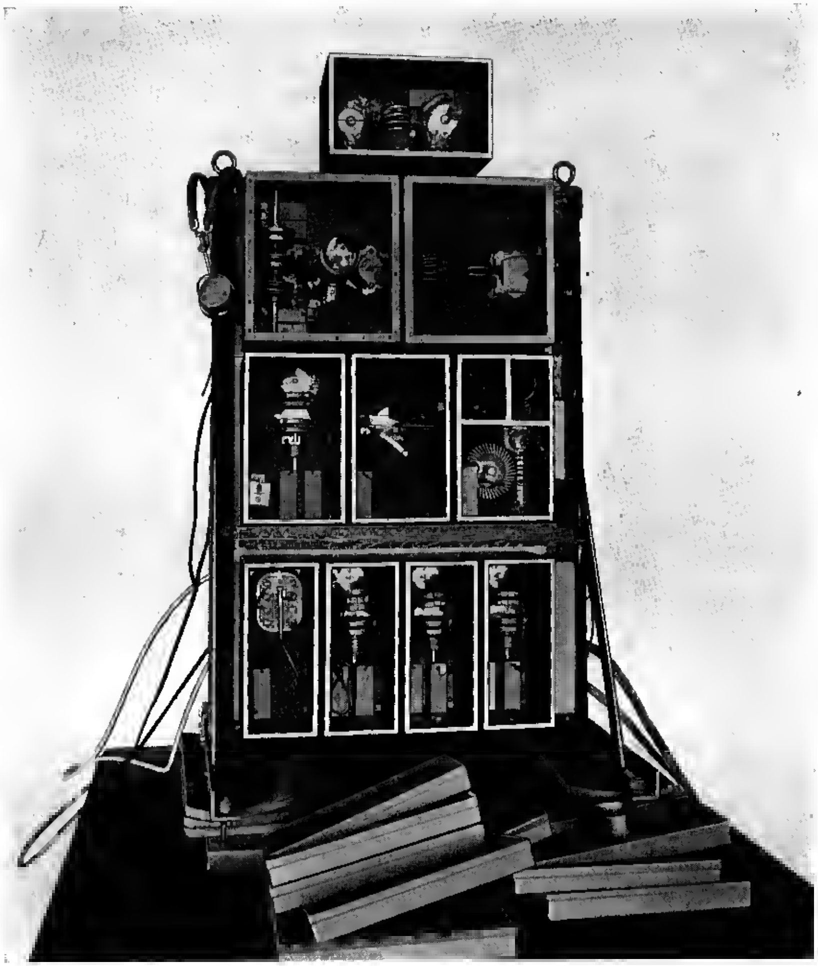

Fig. 1b—Rear view of measuring set with shielding covers removed.

ohms impedance is not easy to construct. A thermocouple was located at the antenna connection, and the resulting direct current was fed down the transmission line and filtered out by a choke coil—con-

[4] Sterba and Feldman, *Proc. I. R. E.*, vol. 20, p. 1163, Fig. 12; July (1932). *Bell Sys. Tech. Jour.*, July, 1932.

denser unit to operate the antenna meter. The antenna current was of the order of 0.6–0.8 ampere ordinarily.

For the entire northwestern half of the horizon the nearby Mt. Pleasant hills screened the country beyond from direct radiation components. The reception in these directions was thus entirely a diffraction phenomenon. Fig. 2 gives the result of a cross-country transit

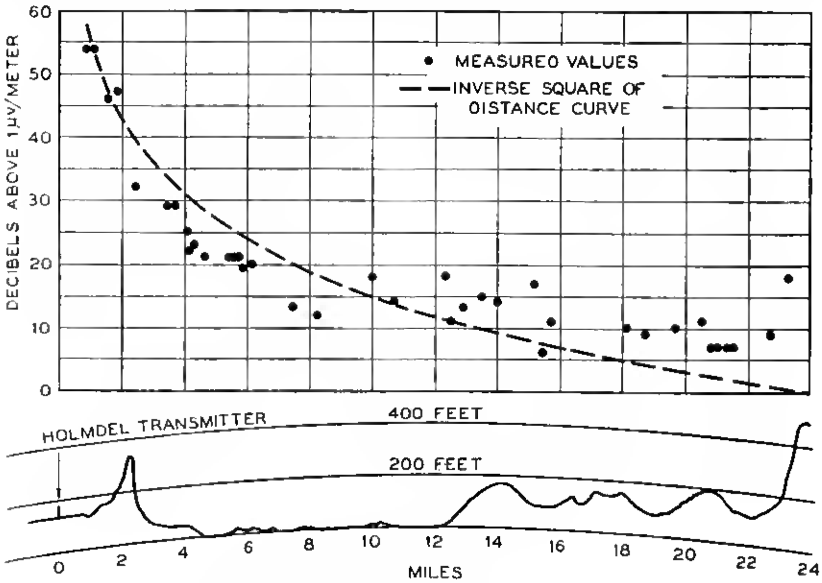

Fig. 2—Transmission along radial line from Holmdel laboratory to Watchtung Mountains.

out beyond these hills. The wave-length was 4.6 meters and at each point the field intensity was obtained by averaging over several maxima and minima. As closely as possible a fixed direction was maintained. The field strengths were first observed as decibels left in the set attenuator and were afterwards corrected as described in a later paragraph. An inverse square of distance curve is drawn in for comparison purposes. Up to the hills a direct plus a reflected radiation component constitutes the transmission; back of the hill a diffraction phenomenon occurs. The transmitting antenna was vertical and the radiation was received by a short rod antenna projecting through the top of the light truck carrying the receiving set.

The observed values are rather erratic, and later experience has shown that this irregularity may be expected for measurements taken on or at the ground level and that it is due to an almost universal and highly irregular standing wave pattern.

Standing Wave Patterns

This standing wave pattern has not yet been sufficiently studied. It is easy, by driving the receiver car sufficiently slowly, to show that some of the "fringes" are due to reradiation from individual trees along the roadside. Vertical metallic guy wires and other metallic structures are equally good reradiators. The type of interference pattern which would be expected from a reradiating tree is shown in Fig. 3, and this is

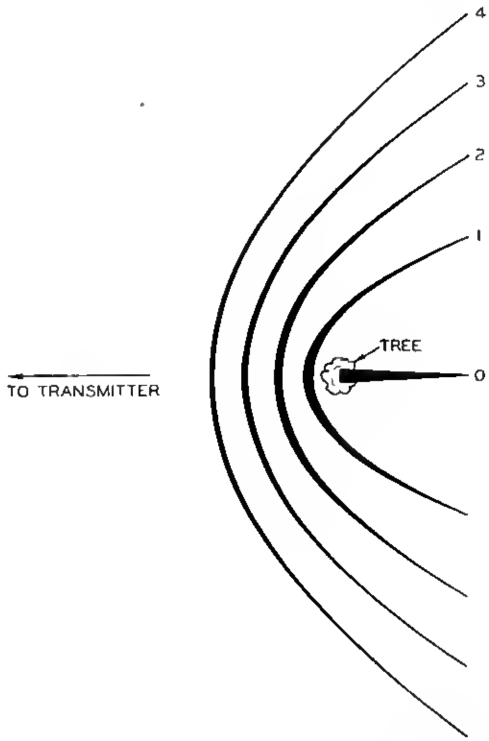

Fig. 3—Standing wave system surrounding a tree. Phase shift on reflection 180 degrees. Curves show first five lines of minimum field.

substantially what was found by driving the receiver car around isolated trees. But in general the pattern is not as simple as this and, what is of more importance, the maximum/minimum ratio may run as high as fifty to one. A road bordered with trees gives a very rough pattern.

An open field of some 20 acres extent was available about a mile (1.6 kilometers) from the transmitter. This field lay on a "bench" about 90 feet (27.5 meters) above the Holmdel laboratory ground

level; the bench slope, and a strip of woods lay immediately in front of the field and on the transmitter side. Covering the entire field was an irregular "fringe" system, the fringe spacing varying something like one to four times the wave-length (4.6 meters). By driving the receiver car back and forth across the field a particularly high field intensity line was located and marked for perhaps a hundred yards (91.5 meters). The car was then placed exactly on the line and the receiving set meter carefully watched for any change in the location of this line. No noticeable shift occurred, and the line was checked on the following day and again several days later. A car movement of one foot (30.5 centimeters) was immediately detected by the receiving set meter. It was necessary each time to drive the car in straight

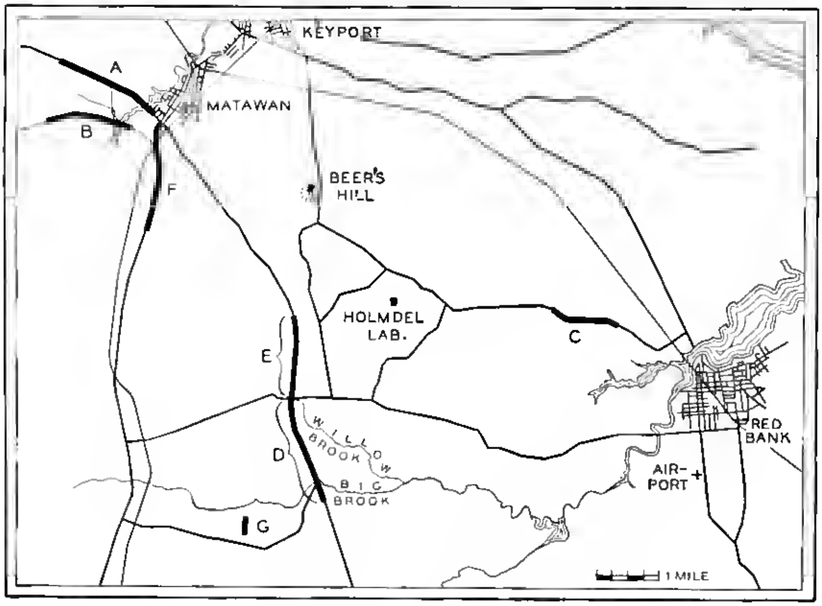

Fig. 4—Map of Holmdel region.

parallel lines since the polar receiving characteristic of the combination of metal car body and radio receiver was not a circle. Opening a car door immediately altered this characteristic. This high field intensity line was not a straight line, being a bit "snaky," and it suffered a shift varying from 2 to 15 feet (0.6 to 4.6 meters) when the transmitting wave-length was changed from 4.6 to 3.7 meters.

These standing wave patterns subside on cleared hilltops and need not therefore seriously affect actual ultra-short-wave channels. They have not been studied by us at distances much exceeding 10 miles (16

kilometers) from the transmitter but they no doubt exist at all ranges. It is certain that both reradiating trees and ground irregularities produce them. By mounting the receiving set with manual recorder in a light truck equipped with superballoon tires we have been able to obtain continuous records of field strength as the truck is slowly (2 to 5 miles per hour) driven along the roads in the neighborhood of the transmitter. Seven of these records and a map of the country are given in Figs. 4 to 6. The records are made by recording the variation in set gain necessary to hold the set output constant versus the distance traversed. They have all been reduced to decibels above one microvolt per meter. The transmitter site was the Beer's hill one, later described, and the records were obtained this year. They are all for a vertical transmitting antenna; the corresponding results for a horizontal antenna are complicated by the almost universal presence of horizontal conductors along the roads. These wires scarcely affect vertical transmission.

As the map indicates, the seven records were taken at distances from two to six miles (air line) from the transmitter. Six were taken along public highways, the seventh was taken in a private field. Of the six, five were taken along roads substantially radial to the transmitter, the sixth along a tangential road.

Record "*A*" was taken along a new road running northwestward from Matawan, N. J. The direction of feed of these records is from left to right, and the arrow indicates that the car was driving northwestward, away from the transmitter. This is a radial road and, being new, is not bordered by straggling trees. It covers 1.7 miles of gently rolling country without steep cuts.

A correspondence of field intensity with topography is to be expected, the favorable addition of direct and reflected radiations being facilitated on slopes facing towards the transmitter and being militated against on slopes facing away from the transmitter. Since the slopes are often short this will put the field maxima near their tops and this is what is found. This record shows this effect perhaps better than any of the others; a profile of the land is included. Profiles are not drawn in on the remaining curves as the country is mostly so irregular that profiles are misleading. Where this topographical coincidence occurs it is noted on the curve.

As the set is carried past them, trees, wired houses, and the like make their presence known on the record. Extended areas of trees, as woods and orchards, usually involve a marked absorption of signal intensity which, however, does not extend much beyond their boundaries.

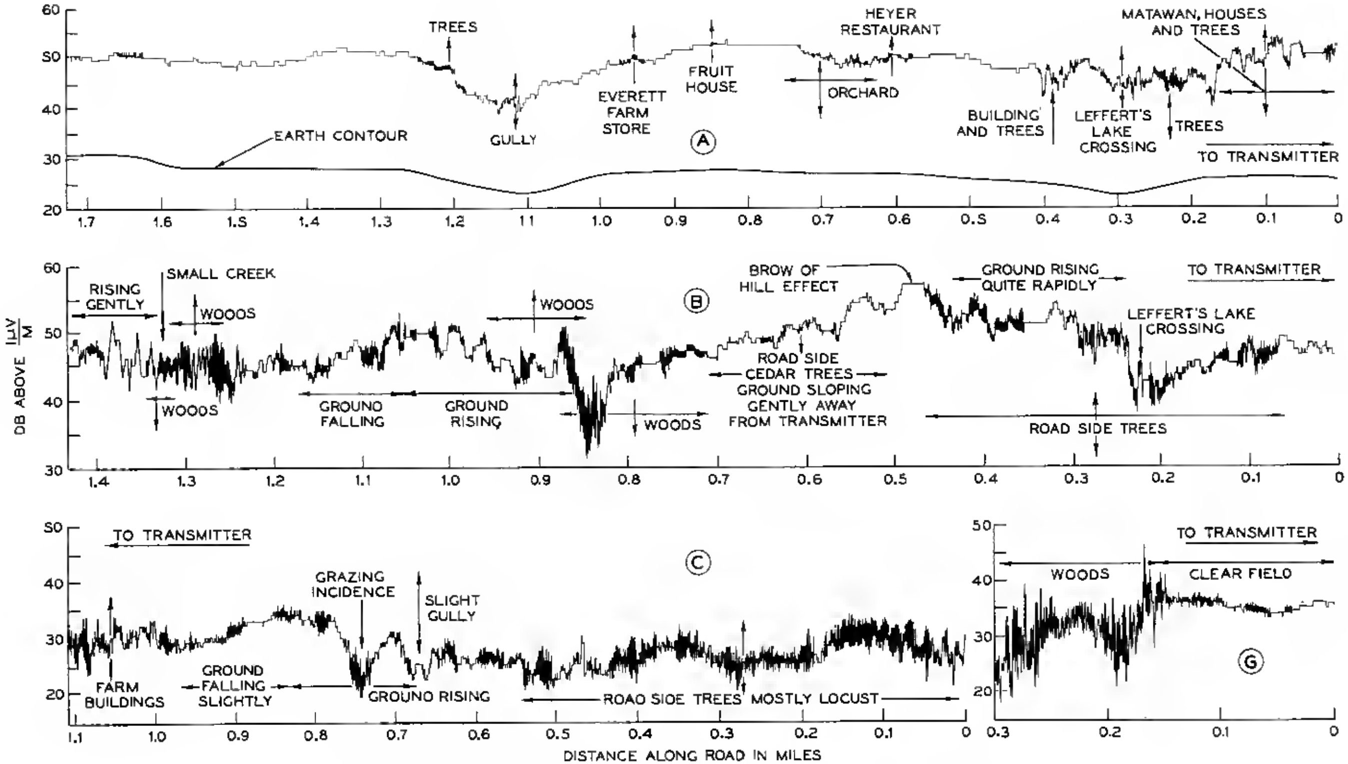

Fig. 5—Four diffraction patterns taken along lines radial to transmitter.

"A" radial 2.54–4.25 miles from transmitter 8–25–'32.
"B" radial 2.94–4.29 miles from transmitter 6–23–'32.
"C" radial 4.25–5.3 miles from transmitter 6–16–'32.
"G" radial 6–23–'32.

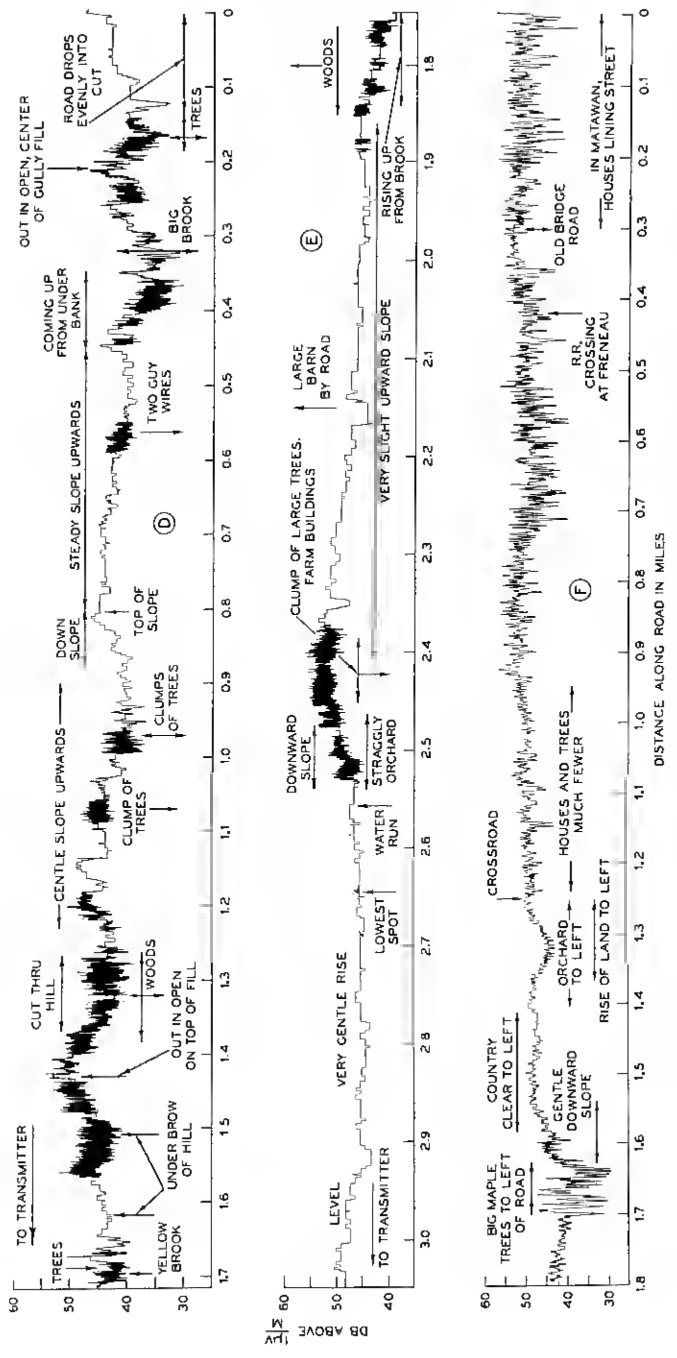

Fig. 6—Three diffraction patterns, two taken along lines radial to transmitter, one along a line perpendicular to transmitter direction.

"D" radial 3.28–4.95 miles from transmitter 6–15–'32.
"E" radial 2.0 –3.28 miles from transmitter 6– 8–'32.
"F" tangential 2.6–2.7 miles from transmitter 8–25–'32.

Record "*B*" was taken along another radial road not far distant and roughly parallel to that of "*A*." This is an old road and has the usual string of nondescript trees along the road edges. These trees roughen up the pattern always, sometimes badly, but the ground slope changes can usually be identified (compare with the previous record). The marked maximum at 0.47 mile, where direct and reflected radiations add favorably, is the equivalent of the "brow-of-hill effect" found for short waves.[5] The very marked undulation at 0.85 mile is apparently due to the overlapping of two extensive patches of woods which here, for a short distance, blanket both sides of the road. In the written comment on the records the direction of the arrows indicates the side of the road on which the objects mentioned lie.

Record "*C*" is that for a radial road southeast of the transmitter. This is an old tree-bordered road and has several turns in it. The trees are mostly locust and there are quite a few vertical guy wires on the power and telephone poles. In the pattern these guy wires are usually indistinguishable from trees. The correspondence with topography appears in several places, but there is an unexpected and deep minimum at 0.74 mile. There are no trees or other objects to explain this, and our feeling is that it is due to a topographical peculiarity whereby the direct and reflected radiations nearly cancel. The road is rising here, in a cut about four feet deep, and in the direction of the transmitter the ground billows up so that one can visualize the explanation given.

Records "*D*" and "*E*" were taken along a new radial road (an extension of "*A*," in fact New Jersey highway No. 34). At the right of "*D*" the road starts downward towards the transmitter at the same time entering a cut. There are no trees and the resulting record is a fast dropping smooth one. Farther on the marked effects of a pair of guy wires and some clumps of trees can be seen; the absence of other trees giving an undisturbed background to work against. A favorable slope, or "brow-of-hill" effect, is seen at 1.43 miles. The latter part of the record is through a succession of cuts and fills, with trees about, and the record is correspondingly rough.

Record "*E*" continues the previous record. There is an initial rise at the start, due to rising ground, and woods to the right roughen up the pattern. From here on to the end there is a slow ground rise, a slight fall, and a final rise. At the center of the stretch is an isolated clump of trees with farm buildings and a straggly orchard below. The contrast between the treeless stretch and that with trees is very marked. The effect of the trees begins suddenly, at about 150 feet in from the edge of the grove.

[5] Potter and Friis, *Proc. I. R. E.*, vol. 20, p. 699; April (1932).

Record "*F*" is that of a tangential run along the old Matawan-Morganville road. Starting in the town of Matawan, with houses and trees about, the pattern irregularities subside slowly, as these objects decrease in number, up to 0.95 mile. At 1.26 miles a rise of ground to the left (transmitter side) is covered with an orchard. Apparently the unfavorable slope is more potent than the trees in reducing field intensity, as the field falls and rises more in accord with this land rise than with the orchard. At the end of the record some large old maples on the transmitter side of the road roughen up the pattern very markedly.

Record "*G*" is a short run taken on a private road where the car was run in from a cleared field into woods.

Field Fluctuations from Moving Bodies

It is well known that the motion of conducting bodies, such as human beings, in the neighborhood of ultra-short-wave receivers produces readily observable variations in the radio field. This phenomenon extends to unsuspected distances at times. Thus, while surveying the field pattern in the field described above, we observed that an airplane flying about 1500 feet (458 meters) overhead and roughly along the line joining us with the transmitter, produced a very noticeable flutter, of about four cycles per second, in the low-frequency detector meter. We then made a trip to the nearby Red Bank, N. J., airport, distant about 5½ miles (8.8 kilometers) and observed even more

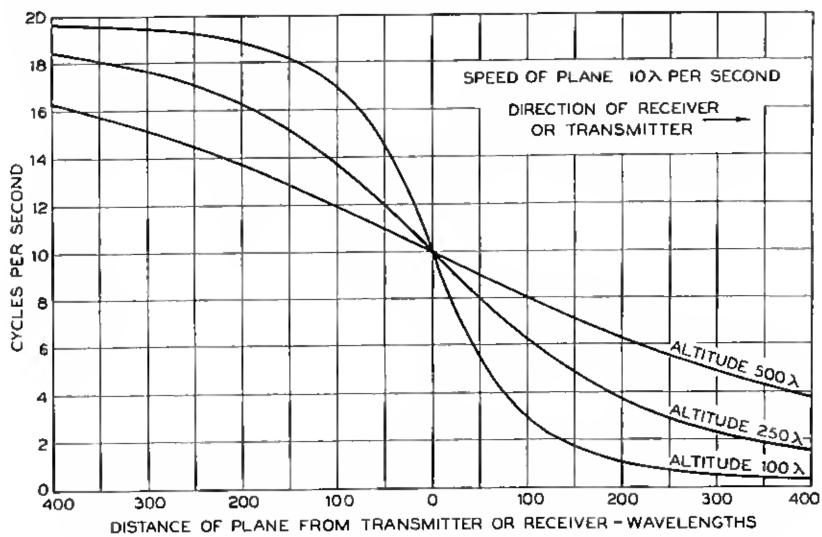

Fig. 7—Beat frequencies produced by reflection from a moving airplane.

striking reradiation phenomena. Nearby planes gave field variations up to two decibels in amplitude, and an airplane flying over the Holmdel laboratory and towards this landing field was detected just as the Holmdel operator announced "airplane overhead." These were all fabric wing planes. If the reradiation field to which such an airplane is exposed is of inverse distance amplitude type while the directly received ground fields are of more nearly inverse distance square type, as in Fig. 2, it is easy to see that at five miles an overhead airplane is exposed to a field intensity about ten times (20 decibels) that existing at the ground, and for ordinary airplane heights a high energy transformation loss in the reradiation process can occur and still give marked indications in the receiver meter. This airplane reradiation was noticed at various subsequent times, sometimes when the airplane itself was invisible. A set of theoretical beat frequency versus distance curves are given in Fig. 7.

Air-Line Transmission

While ordinary ultra-short-wave transmission is complicated by local reradiations and diffraction phenomena these should become relatively innocuous for favored locations such as hilltop-to-hilltop transmissions with the air-line path between them clearing all intervening obstacles. Here the presence of fading, day-to-night changes in transmission, amount of static interference, and the rôle of the earth-reflected radiations should be determinable. After some days of rough surveying such a pair of hilltops was found 39 miles (63 kilometers) apart. We would have preferred a greater distance but none such could be located with certainty, with one of the hills necessarily local.

The transmitter was mounted on this local hilltop, Beer's Hill, two miles (3.2 kilometers) air line to the north northwest of the laboratory. The apparatus consisted of a 40-foot (12.2-meter) lattice mast with nonmetallic guys, mounting a half-wave linear antenna which could be rotated between a vertical and a horizontal position. A low impedance (246-ohm) transmission line, similar to the one earlier described, carried the ultra-short-wave current from the generator shack at the foot of the mast to the antenna itself. The termination and method of antenna current indication were as described for the Holmdel laboratory transmitter. The hilltop altitude (U. S. Bench Mark) was 343 feet (104.6 meters) and the antenna was thus 383 feet (116.8 meters) above sea level.

The receiver site was located on a hill spur on the P. K. McCatharn farm $2\frac{1}{2}$ miles north of Lebanon, N. J., and at an altitude of 750 feet (228.5 meters). Taking the altitudes from the New Jersey geological

survey maps and correcting for earth curvature gives the profile map of Fig. 8, where it is seen that the air line clears the intervening country everywhere by 200 or more feet (61 meters). We were unable to check this by direct optical observations as no sufficiently clear day occurred during our tenure of the Lebanon site but we were able to identify a neighboring hill of about the same altitude (Mt. Cushetunk) and we have no doubt that an air-line path existed.

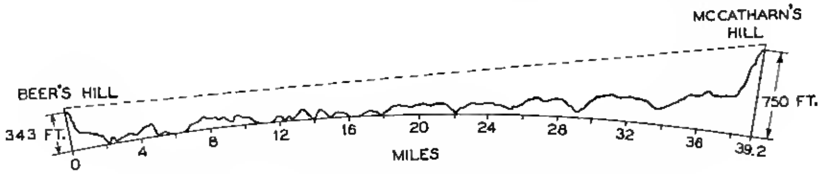

Fig. 8—Profile map. Beer's Hill to McCatharn's Hill.

If we imagine a transmitting and receiving antenna pair located above the earth's surface it is easy to see that the received radiation will consist of a direct plus a reflected component. If now we complicate matters by adding a pair of hills to support the antennas we shall add a pair of reflections from the slopes of the two hills to the initial two radiation components. A final random corrugation of the earth and we have the actual Holmdel-Lebanon situation. The conditions under which the first reflection occurs, practically grazing incidence, with the earth irregularities very small compared with the optical path length, make it very certain that this reflection will substantially survive the corrugation; the proximity of the hills to the antennas themselves ensures the presence of the second pair of reflections. The actual transmission should thus consist of a direct component plus a three-surface set of major reflection components, together with a background of scattered and diffracted radiation arising from the corrugations of the earth's surface. For an extreme path length the lens effect of the earth's atmosphere, decreasing in density upwards and thus refracting the entire radiation ensemble downwards, will produce a path deviation which cannot be neglected.[6]

A verification of this radiation picture should be possible. The hillside reflection components can be demonstrated by separately raising and lowering the two antennas. Inasmuch as the reflections occur nearby, only a small movement of an antenna is required to vary the path difference between the direct and reflected rays by half a wavelength and thus vary the received signal intensity through a maximum-to-minimum, or reversed, cycle. The earth reflection occurs sub-

[6] Pedersen, "Propagation of Radio Waves," chap. X, p. 150. The importance of this refraction effect has most recently been pointed out by Schelleng, Burrows, and Ferrell, companion paper in this issue of *Bell Sys. Tech. Jour.*

stantially halfway between the antenna sites, and very great altitude changes become necessary to exhibit a maximum-to-minimum cycle. This reflection component cannot thus be demonstrated from two hill locations such as we had; but one of the hills together with a receiver carried by an airplane will suffice. We were able thus to demonstrate all the three main reflections.

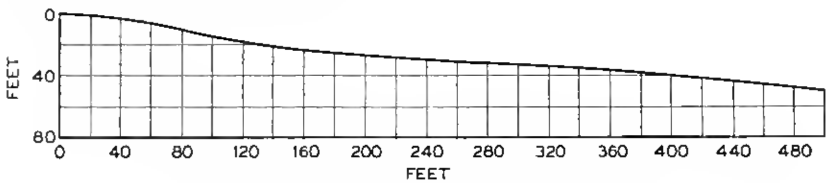

Fig. 9—Profile map of McCatharn's Hill.

Fig. 9 gives a profile of the McCatharn Hill along the radio transmission line and Figs. 10 and 11 show the received field strength

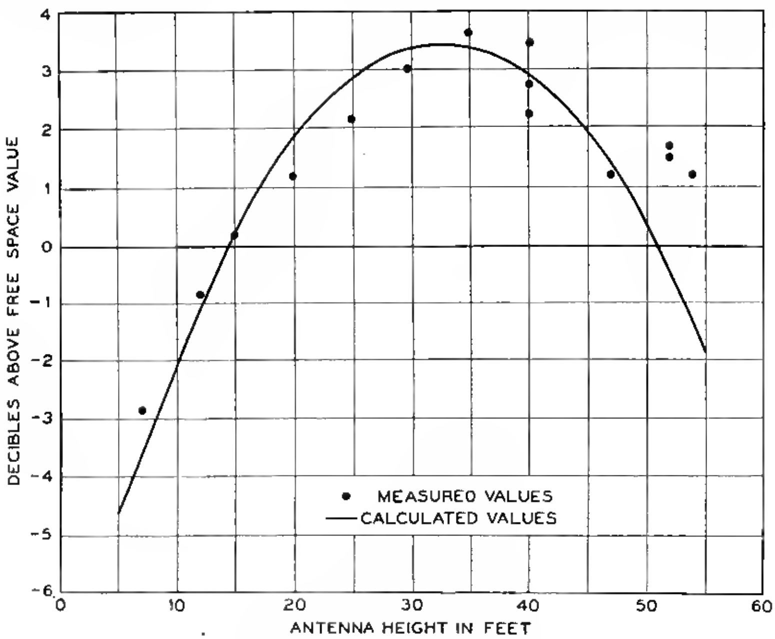

Fig. 10—Local reflection at McCatharn Hill. Vertical polarization $\lambda = 4.08$ meters.

variation as the antenna was raised and lowered [7] for both horizontally and vertically polarized radiations. Assuming this hill to be a medium

[7] The receiving set, in the truck, was located on the hilltop after making sure that stationary diffraction fringes were of negligible amplitude. By permission of

of dielectric constant 10 and resistivity 10,000 ohms per cm. cube, and to have a plane reflecting surface inclined to the horizontal at an angle of 5.9 degrees, reception curves for an antenna raised and lowered over

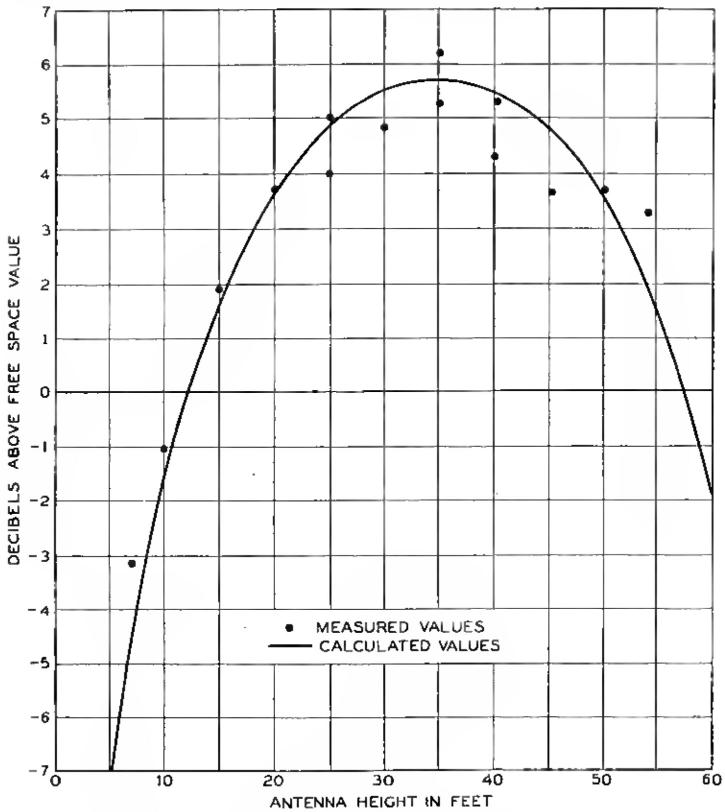

Fig. 11—Local reflection at McCatharn Hill. Horizontal polarization $\lambda = 4.39$ meters.

it have been calculated and are compared with the experimental results. These measurements, being relative only, have been adjusted to best coincidence by adding the necessary decibels. The resulting fit is fairly good. A quantitative comparison between theory and experiment is later given.

the owner, some trees below the hill were cut down to clear the radiation path. The antenna structure was a 40-foot lattice mast with a boom carrying the antenna itself and extending fifteen feet above the mast top. The transmission line was incandescent lamp cord (a twisted pair of rubber and cotton insulated conductors) and was tied to boom and mast so as not to swing. It had a measured loss (erected and measured at Holmdel) of 0.1 decibel per foot. The boom swung in an arc in a plane perpendicular to the line of transmission. No evidence of a rotation of the plane of polarization was observed.

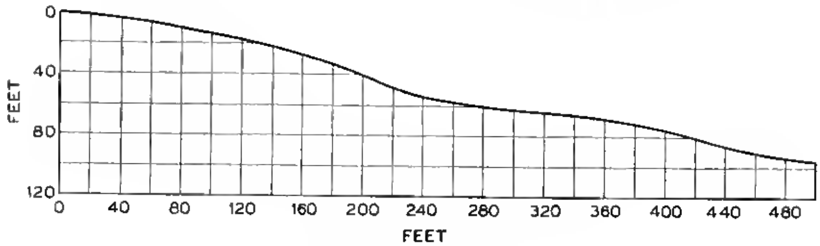

Fig. 12—Profile map of Beer's Hill.

With a sufficiently plane slope a maximum-to-minimum field comparison should yield a dependable value of the amplitude of the reflection coefficient since the other two reflection components (transmitter hill and intermediate earth surface) are not rapidly varied by such a limited change in receiving antenna height. Unfortunately the antenna could not be elevated above 55 feet (16.8 meters), and with the moderate hill slope existing, this was insufficient to reach the first above-ground field minimum.

The intermediate earth surface reflection component, at this near-grazing incidence, acts to reduce the total received field, and it is important to obtain an idea of how great this effect is likely to be. It is necessary to rely on the accuracy of the topographical maps as issued

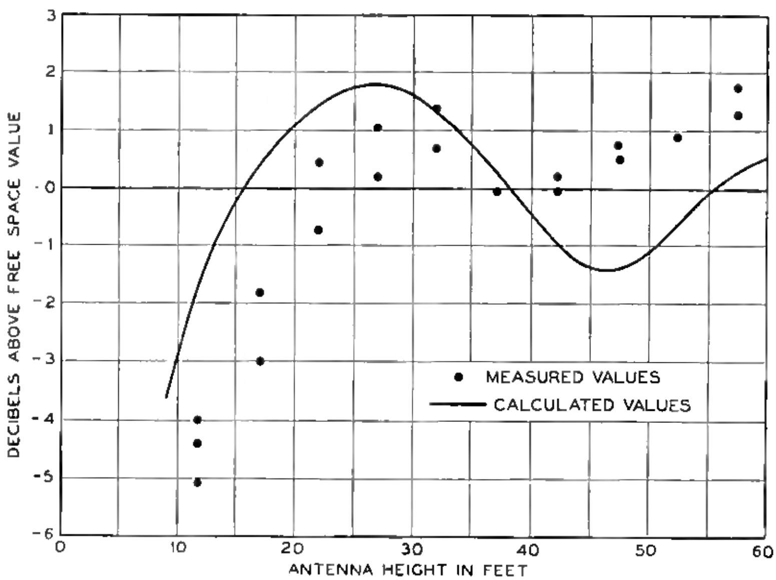

Fig. 13—Local reflection at Beer's Hill. Vertical polarization $\lambda = 4.45$ meters.

by the state of New Jersey but a conservative use of them indicates that at a wave-length of 4.45 meters a phase difference of about 198 degrees exists between the direct and reflected components and the resultant field should be about 31 per cent of that of a simple inverse distance transmission. (The effect of air refraction is included.) This is adequate for good reception at the McCatharn Hill.

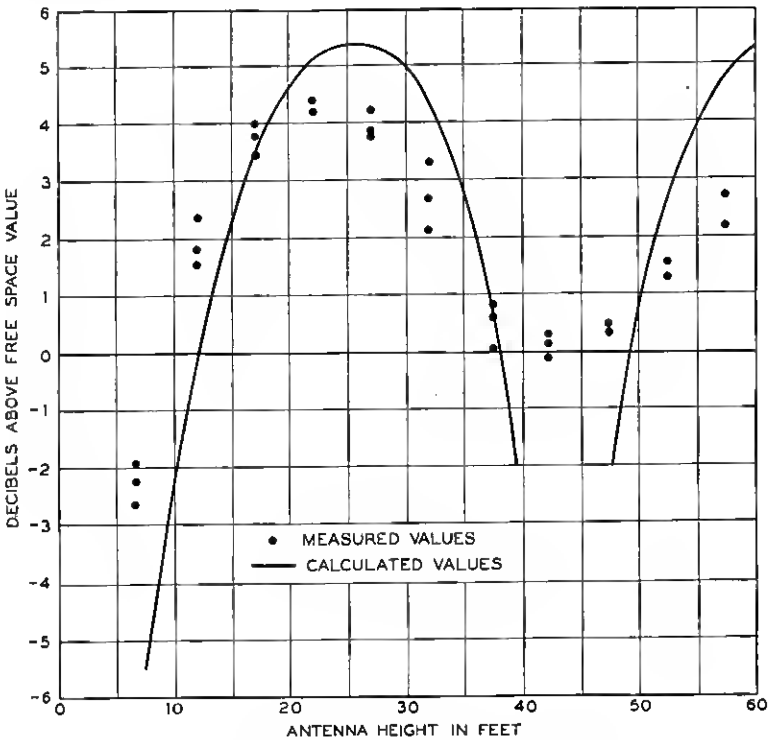

Fig. 14—Local reflection at Beer's Hill. Horizontal polarization $\lambda = 4.45$ meters.

Fig. 12 gives a profile of Beer's Hill along the line of transmission, and Figs. 13 and 14 the McCatharn Hill reception as the transmitting antenna was elevated. The hill slope is steeper here (Beer's Hill) and the curves obtained for the original 40-foot (12.2-meter) structure having indicated that the first off-ground field minimum could be reached with a little more height, an additional 20-foot section was added to the lattice mast making it 60 feet (18.3 meters) high. The difficulty of handling a low-loss bare wire transmission line, as the height was varied, caused us to substitute a twisted pair incandescent

lamp cord for it. In raising and lowering the antenna this transmission line was simply permitted to pile up on the ground. The antenna ammeter showed only small current variations as this coil was handled or pushed about. We originally had some doubts as to whether this hill would give a clean-cut reflection since the surface in the receiver direction was somewhat undulating and had a gully with trees beginning some 200 feet down the hillside. However, as the results indicate, a fairly definite reflection component is produced.

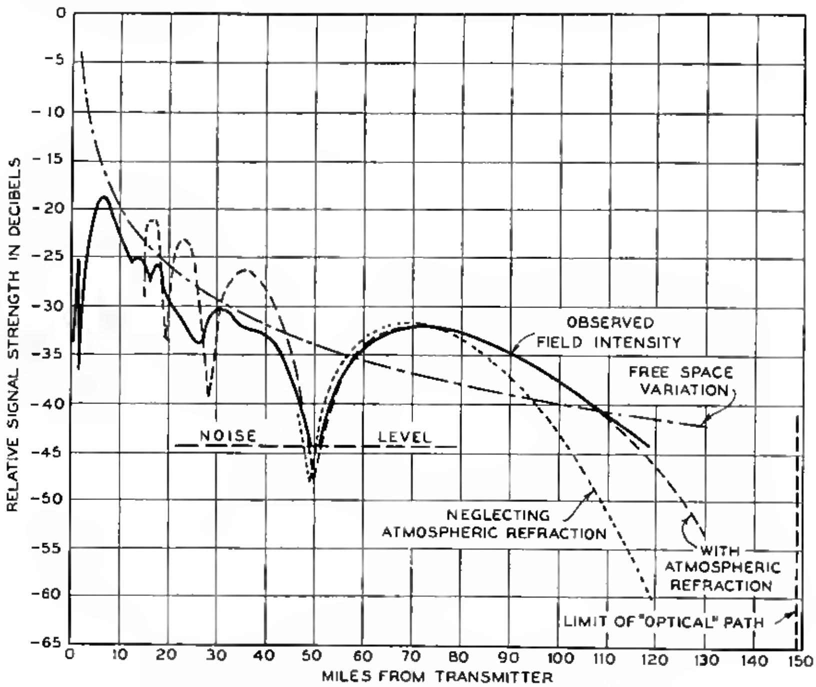

Fig. 15—Flight from transmitter. Altitude—8000 feet; wave-length—4.3 meters, June 24, 1931.

The dots in Figs. 13 and 14 are observed values, the full lines are theoretical curves. These latter were obtained by taking the hill constants the same as for the McCatharn Hill, but the hill itself was not assumed to be a plane. Instead, by graphical plotting from the hill contour, the tangent plane for each antenna height was located and used for the calculation for that height only. The resulting curve is a somewhat better fit than is obtained by averaging the hill to a common plane.

This hill surface, as stated earlier, is a rather poor fit to a plane (the profile cross section shows the hill up too favorably) and has quite a

few trees located on or about the reflection area corresponding to the higher antenna positions. The result is particularly noticeable for the vertically polarized transmission where the fit between observation and experiment is poor. This experiment was later repeated with the same results. The conclusion follows that while the oscillatory character of the field intensity curves indicates a definite local reflection component, it is not as simple as the one arising from a smooth surface by plane optical reflection.

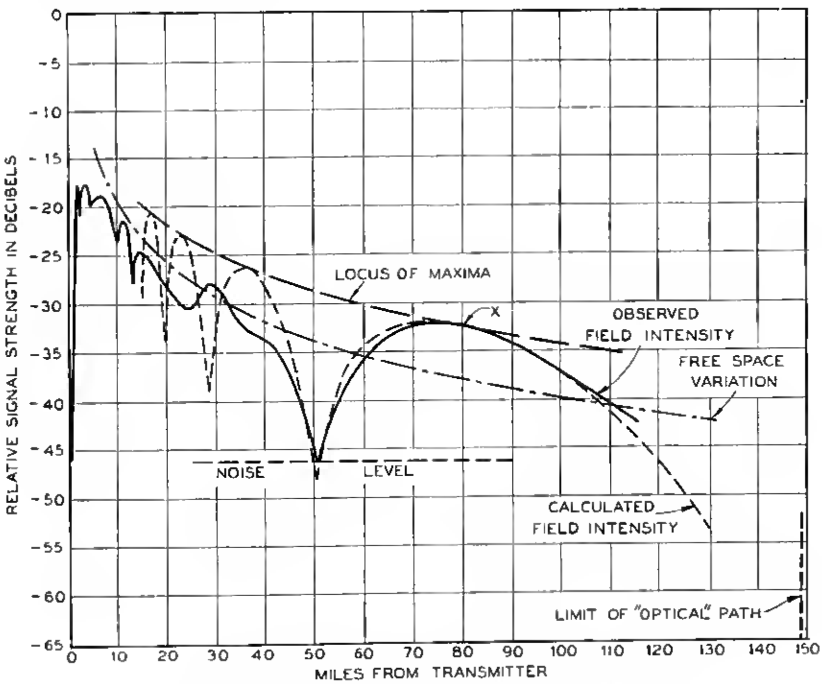

Fig. 16—Flight toward transmitter. Altitude—8000 feet; wave-length—4.3 meters, June 24, 1931.

The middle distance reflection was clearly established by airplane observations. For these only vertically polarized radiation was used, and a simple vertical rod antenna was thrust out of the airplane cabin ceiling. This limited the maximum range which was attained, but antennas of greater effective height were difficult to construct. This plane was the Laboratories' Ford trimotor, and we are indebted to Mr. F. M. Ryan and his staff for their cooperation in this work. The manual recorder already mentioned was used throughout the runs, which were made by flying directly from Beer's Hill to Easton, Pa., and

then veering slightly to the left to follow the main New York-to-Chicago airplane route. Flights were made at 8000, 5000, 2500, and 1000 feet (2440, 1525, 763, and 305 meters) above sea level, and the results are given in Figs. 15 to 20 inclusive. Fig. 21 gives a map of the country.

In these figures the experimental curves are supplemented by theoretical ones, these latter being calculated by assuming the earth at the reflection point to be equivalent to a plane surface medium of a dielec-

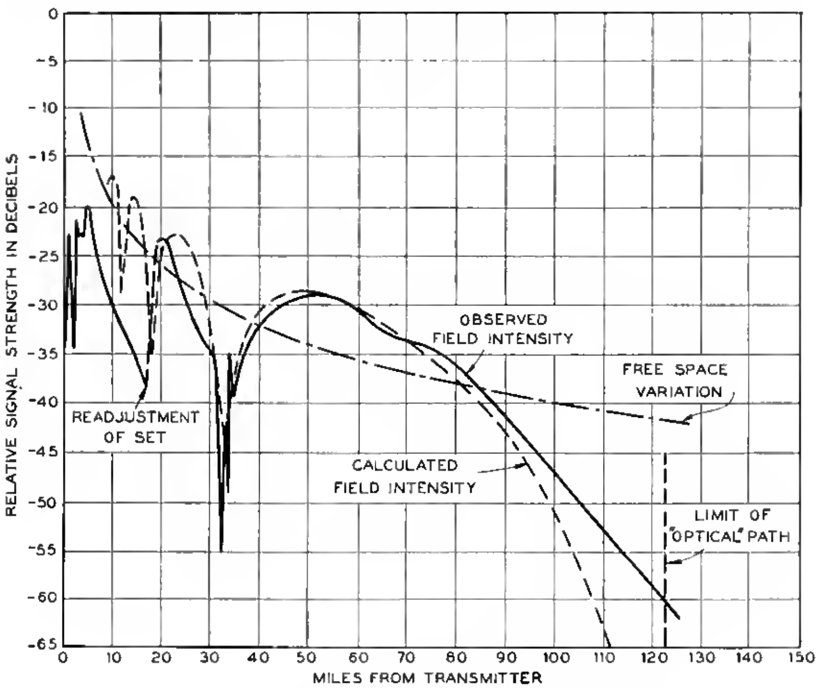

Fig. 17—Flight from transmitter. Altitude—5000 feet; wave-length—4.3 meters, June 29, 1931.

tric constant 10 and a resistivity of 10,000 ohms per cm. cube and 100 feet (30 meters) above sea level. This point, for the outermost deep minimum, varied in location from 1.5 miles out, for the 1000-foot flight, to 2 miles out, for the 8000-foot flight, with corresponding angles of incidence of 88 and 88.5 degrees. The area involved is fairly level and open. The earth's curvature is taken into account and refraction corrections are applied using the Schelleng, Burrows, and Ferrell formula. As shown in Fig. 15 the fit at the extreme distances is considerably improved by this latter correction, thus indicating its validity. The deep

and outermost minimum is due to the middle distance reflection with a 540-degree phase difference. It is unmistakable and definite. The minima corresponding to phase differences of odd numbers of 180-degree angles greater than three are not so clear cut. It is here that the ground corrugations will have the greater destructive effect.

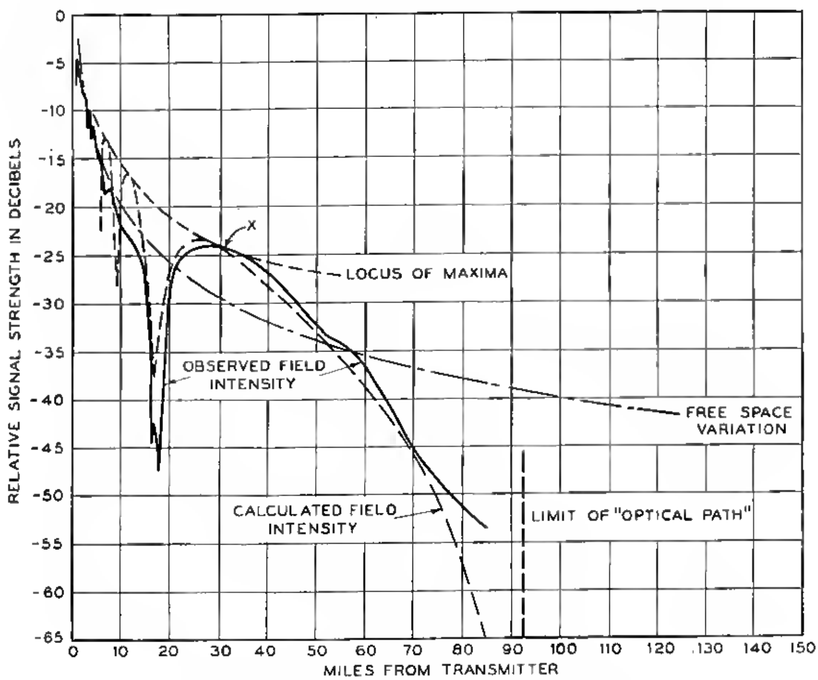

Fig. 18—Flight from transmitter. Altitude—2500 feet; wave-length—4.3 meters, June 26, 1931.

The method of calculation is more fully explained in Appendix I, and the effect of a possible diffraction by Mt. Cushetunk in Appendix II. In the 8000-foot curves ignition noise masked the deep outermost minimum, and in the 1000-foot curve it is poorly defined, but it appears well marked in the 5000- and 2500-foot curves, and is roughly 10 decibels below the theoretical value. This minimal depth corresponds to a reflection coefficient of about 0.92 for this angle of incidence (88.4 degrees); the theoretical reflection coefficient is 0.8.

General Observations

During these experiments no static was observed. It has since been found by Mr. Jansky of the Laboratories that local summer thunderstorms produce noticeable static interference and that such storms may

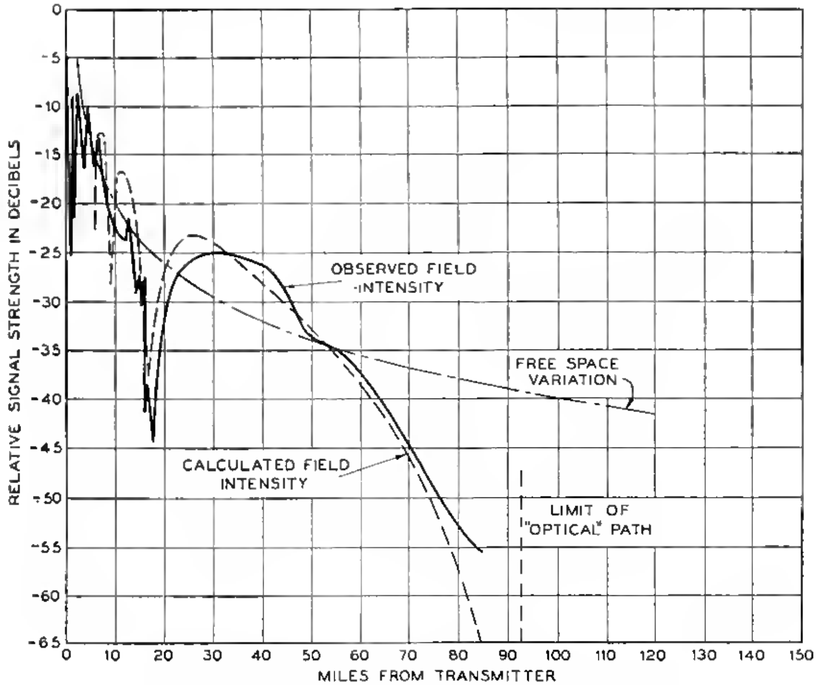

Fig. 19—Flight toward transmitter. Altitude—2500 feet; wave-length—4.3 meters, June 26, 1931.

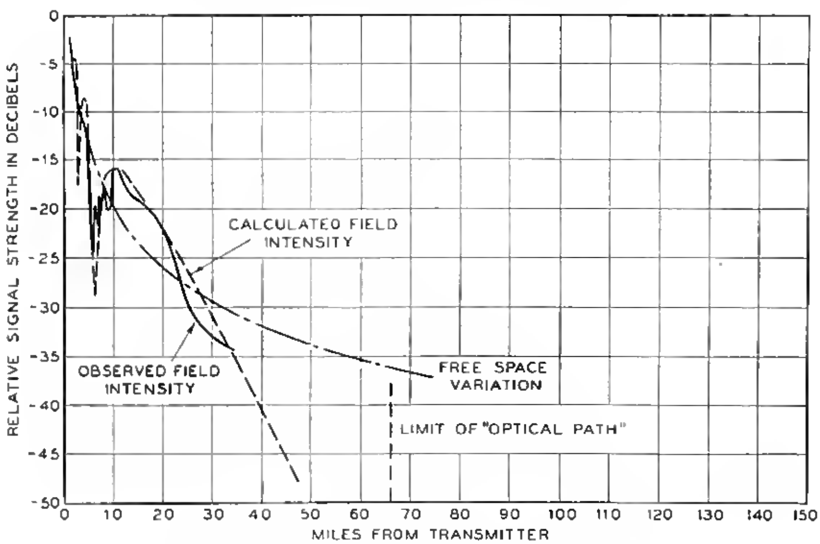

Fig. 20—Flight toward transmitter. Altitude—1000 feet; wave-length—4.3 meters, June 29, 1931.

sometimes be detected up to a distance of 50 miles (81 kilometers). This interference is, however, very much less than on short-wave reception.

One continuous transmission test from Holmdel and Beer's Hill to Lebanon was made April 24 and 25, 1931, extending through the night and over both the sunset and sunrise periods. The Beer's Hill transmission was horizontally polarized, the Holmdel transmission vertically polarized. The wave-lengths were 4.17 and 4.5 meters, respectively. Quarter-hourly observations were taken during the night, and observations were made every five minutes through the sunrise and sunset periods. No signal variations or abnormalities were observed, and harmonics of short-wave stations, though looked for, could not be heard. We have since observed these harmonics, for high power stations, but not from any great distance.

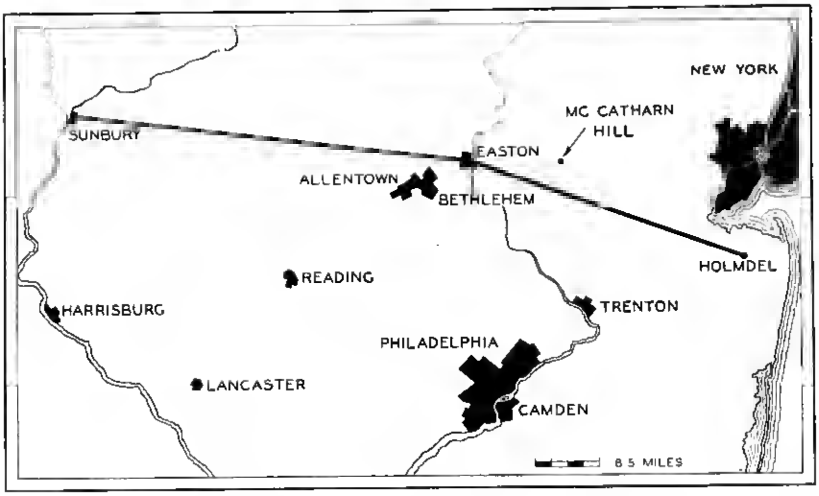

Fig. 21—Map of line covered by airplane flights.

The Beer's Hill transmitter power during all our tests never exceeded 6 watts, and gave an ample signal intensity at Lebanon, in spite of the 198 degree phase difference of the middle distance reflection component. Telephone transmission was uniformly good.

Appendix I

Calculation of Airplane Reception Curves

The resultant field strength at a point in the line of flight (Fig. 22) is

$$E_r = \frac{E_0}{D}\left(1 + Ke^{i[\theta+(2\pi/\lambda)(r_2-r_1)]}\right) \qquad (1)$$

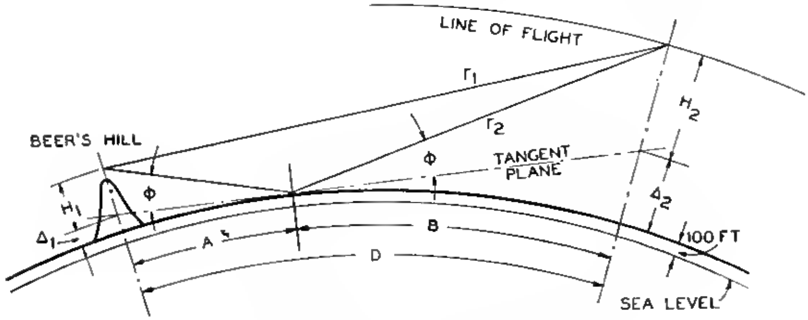

Fig. 22—Geometry of airplane reception.

where,

E_0 = the free space field at distance of 1 mile

K = amplitude change at reflection

θ = phase change at reflection

(K and θ are functions of the angle of incidence and the ground constants)

$(r_2 - r_1)$ = the path length difference between direct and reflected rays.

$$(r_2 - r_1) = \frac{2H_1H_2}{D} = \frac{2AB\tan^2\Phi}{D} \tag{2}$$

provided H_1 and H_2 are small in comparison with D.

H_1 and H_2 are the heights of transmitter and receiver above the plane tangent to the earth at the point of reflection.

The height of the tangent plane above the earth's surface is

$$\Delta_1 = R\left(-1 + \sqrt{1 + \frac{A^2}{R^2}}\right) = \frac{A^2}{2R}\ \text{(app.)} \tag{3}$$

and,

$$\Delta_2 = \frac{B^2}{2R}\cdot$$

R is the radius of the earth, which, due to atmospheric refraction, is taken to be 5260 miles,[8] an increase of 33 per cent over the actual radius. $(H_1 + \Delta_1)$ is always 280 feet, the height of the transmitting antenna above the reflecting surface, which, in the case at hand, is about 100 feet above sea level.

$(H_2 + \Delta_2)$ is constant for any flight at constant altitude.

For any value of A, H, and hence $\tan\Phi$ may be calculated and plotted as in Fig. 23. In this figure B is also plotted, for a flight at 8000 feet, against $\tan\Phi$. The total distance D is obtained by adding

[8] Schelleng, Burrows, and Ferrell paper, this issue of *Bell Sys. Tech. Jour.*

A and B at constant tan Φ. Thus, for any distance of the plane, we can read from the curves the values of A, B, and tan Φ, and can calculate the path difference $(r_2 - r_1)$ by equation (2).

In this manner, the theoretical reception curves, which are given in Figs. 15 to 20 (dotted curves), were calculated for flights at 8000, 5000, 2500, and 1000 feet. The ordinate "Relative Signal Strength—Decibels," is 20 $\log_{10} E_0/E_r$, and gives the received signal strength in decibels below the field strength in free space at a distance of one mile from the transmitter.

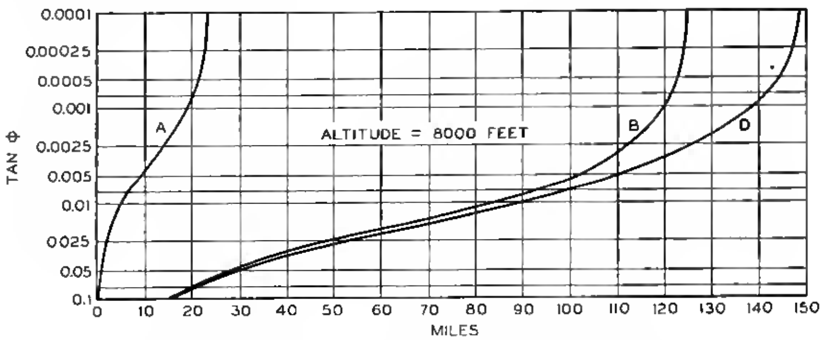

Fig. 23—Sample curve for calculating airplane results.

Since the scale of the observed reception curves is unknown, they are superimposed upon the calculated ones by causing the maxima of the observed curves to coincide at some point with the theoretical loci of maxima (see for example, the points marked "x" in Figs. 16 and 18).

In the limit, as grazing incidence is approached, the theoretical reception approaches zero. In equation (1), K becomes unity and θ becomes 180 degrees and the path length difference $(r_2 - r_1)$ becomes zero. The observed field at distances greater than those required for grazing incidence is a diffraction one.

Appendix II

Diffraction Calculations

In Fig. 25 the data of Fig. 17 for the 5000-foot airplane flight are compared with a theoretical curve which has been corrected from that of Fig. 17 by considering a possible diffraction around Mt. Cushetunk. This hill, 650 feet high, is 36 miles from Beer's Hill along the line of flight, and is the first major obstruction to an optical path at the greater airplane distances. For this calculation the points of reflection, angles of incidence, and path length differences are determined in the manner described in Appendix I, just as if the hill were absent. The

hill is then introduced in the picture and, considering it as a straight edge, its effect on both direct and reflected rays is calculated. (See Fig. 24.)

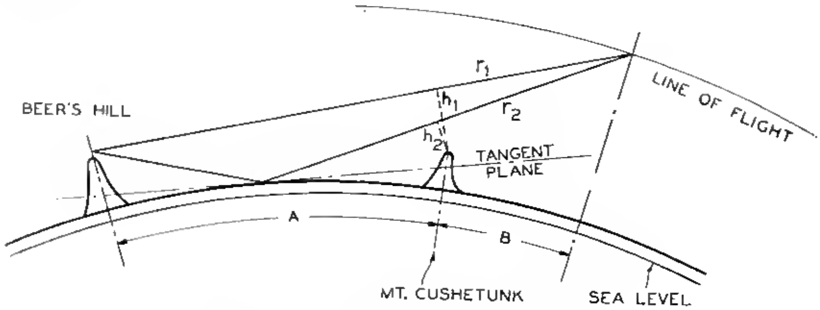

Fig. 24—Diffraction by Mount Cushetunk.

The resultant field at the receiver is then,

$$E_r = \frac{E_0}{(a+b)}\left[F_1 + KF_2 e^{i[2\pi/\lambda(r_2-r_1)+\theta+\beta_2-\beta_1]}\right] \tag{4}$$

where,

F_1 = amplitude change in the direct ray due to diffraction
F_2 = amplitude change in the reflected ray due to diffraction
β_1 = phase change of the direct ray produced by diffraction
β_2 = phase change of the reflected ray produced by diffraction
K = amplitude change due to reflection at the ground
θ = phase change at reflection
E_0 = free space field strength at distance of one mile.

The amplitude factors F_1 and F_2 and the phase changes β_1 and β_2 may be calculated from the Fresnel integrals to the parameter "v" (see note at end), where

$$\begin{aligned} v_1 &= h_1\sqrt{\frac{2}{\lambda}\left(\frac{1}{a}+\frac{1}{b}\right)} \\ v_2 &= h_2\sqrt{\frac{2}{\lambda}\left(\frac{1}{a}+\frac{1}{b}\right)} \end{aligned} \tag{5}$$

"h_1" and "h_2" are the heights of the direct and reflected rays above the straight edge.

"a" and "b" are distances from the straight edge to transmitter and receiver.

A comparison of Figs. 17 and 25 shows that by taking account of diffraction around Mt. Cushetunk better agreement of calculated and observed curves is obtained. However, at grazing incidence this simple theory is inadequate; in this case $F_1 = F_2$, $\beta_1 = \beta_2$, $K = 1$,

$\theta = 180$, and the resultant field strength is zero as in the reflection case treated above.

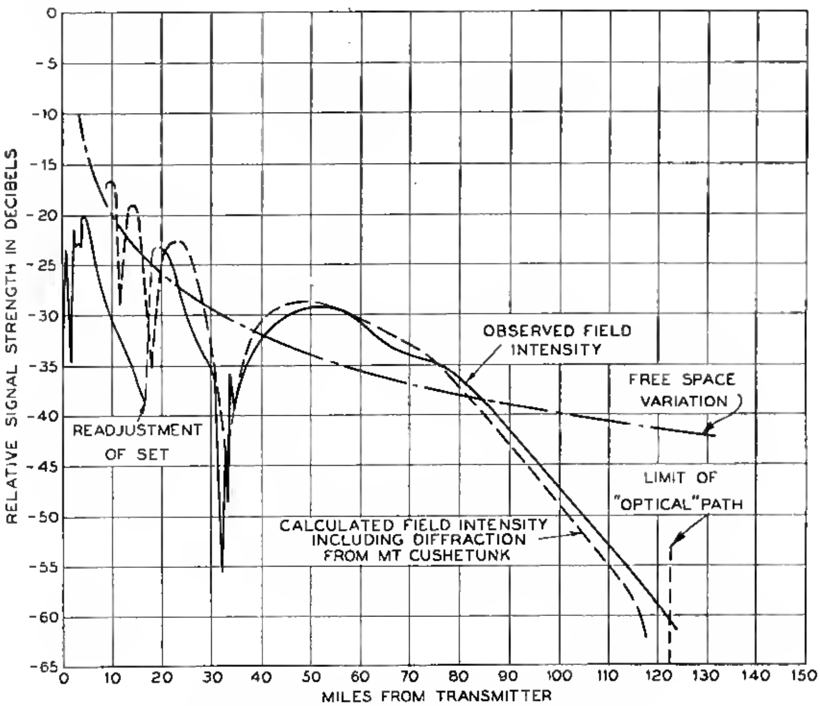

Fig. 25—Flight from transmitter. Altitude—5000 feet; wave-length—4.3 meters, June 29, 1931.

For large values of v_1 and v_2, that is for h_1 and h_2 large, F_1 and F_2 approach unity, and β_1 and β_2 approach zero. Equation (4) then reduces to the ordinary reflection case of equation (1).

Note: The ratio of the diffracted field strength to the field with edge removed is

$$Fe^{i\beta} = \frac{1}{\sqrt{2}}(C + iS)$$

where,

$$C = \int_{-\infty}^{v} \cos\frac{\pi v^2}{2}\,dv = \frac{1}{2} + \int_{0}^{v} \cos\frac{\pi v^2}{2}\,dv$$

$$S = \int_{-\infty}^{v} \sin\frac{\pi v^2}{2}\,dv = \frac{1}{2} + \int_{0}^{v} \sin\frac{\pi v^2}{2}\,dv$$

and,

$$F = \frac{1}{\sqrt{2}}\sqrt{C^2 + S^2}.$$

Appendix III

Quantitative Check on the Beer's Hill-McCatharn Hill Transmission

The Beer's Hill antenna was set at the height of 22 feet, and the receiver taken to the McCatharn Hill where it was operated out of a portable antenna 18 feet high. The optimum height here was 35 feet, and to reach it a more elaborate antenna would have had to be erected. The height used was just as good for a quantitative check as the optimum height. The effective radius of curvature of the earth's surface, corrected for air refraction, is taken as 5260 miles.

Intermediate Reflection Component

Beer's Hill antenna	365 feet above sea level
Intermediate reflection surface	67 feet above sea level
McCatharn Hill antenna	768 feet above sea level.

Referring to the equations of Appendix I, we have

$$\begin{cases} D = 39.2 \text{ miles} \\ A = 13.7 \quad `` \\ B = 25.5 \quad `` \end{cases} \qquad \tan \Phi = 0.00278$$

and path difference between direct and reflected rays

$$= \frac{2AB \tan^2 \theta}{D} = 0.727 \text{ feet, or at } 4.45$$

meters wave-length an equivalent phase difference of 17.9 degrees results.

The angle of incidence is $90 - \Phi = 89.84$ degrees and hence

$$\begin{aligned} K &= 0.977 \text{ for vertical polarization} \\ &= 1.0 \text{ for horizontal polarization} \\ \theta &= 180 \text{ degrees for both polarizations.} \end{aligned}$$

Adding the middle distance reflected component to the free space field "E_0", we obtain

$$E = E_0(1 + Ke^{i197.9°})$$

and,

$$\begin{cases} \dfrac{E_v}{E_0} = 0.308 = -10.24 \text{ db} \\ \dfrac{E_H}{E_0} = 0.311 = -10.14 \text{ db.} \end{cases}$$

Local Hill Reflection Components

By the same process as for the above, and taking the geometry of Figs. 9 and 12 we obtain the site gains,

Beer's Hill reflection, vertical polarization	+ 1.5 decibels
Beer's Hill reflection, horizontal polarization	+ 5.1 decibels
McCatharn Hill reflection, vertical polarization	+ 0.68 decibel
McCatharn Hill reflection, horizontal polarization	+ 2.76 decibels

giving finally:

Vertical polarization transmission 8.1 decibels below free space transmission.

Horizontal polarization transmission 2.3 decibels below free space transmission.

Measured Field Values

The actual field intensity measurements were made using a split half-wave antenna with a transmission line which gave a total loss of about one decibel. Knowing the radiation resistance of antenna and grid circuit input impedance, the transfer voltage ratio could be calculated, and from the grid-to-grid over-all amplification of the receiver the voltage step-up for a given set output determined. The field intensity in microvolts per meter was thus obtained. The measured values were

Vertical polarization	21.6 microvolts per meter
Horizontal polarization	38.5 microvolts per meter.

The transmitter antenna current was 0.05 ampere, and the free space field to be expected at 39.2 miles equal to 47.5 microvolts per meter.

Summarizing the results we have:

Predicted vertical polarization	+ 8.1 db below free space field.
Measured vertical polarization	+ 6.8 db below free space field.
Predicted horizontal polarization	+ 2.3 db below free space field.
Measured vertical polarization	+ 1.8 db below free space field.

The measured values are thus within 16 and 6 per cent, respectively, of the calculated values, a satisfactory agreement.

Appendix IV

We have given three methods of field intensity measurement a trial. These are:

1. Comparison of field intensity with the mean first circuit noise voltage of the receiver. As shown by Johnson [9] the latter can be calculated, and by knowing the transfer voltage factor of the antenna-transmission line-input circuit combination and the difference in receiver set amplification for the two voltages the field intensity can be calculated.

2. Local oscillator comparison.[10] Here a local oscillator, with a

[9] Johnson, *Phys. Rev.*, vol. 32, p. 97 (1928).

[10] Described in the Schelleng, Burrows, and Ferrell paper.

small loop antenna is mounted in the neighborhood of the set, precautions being taken to keep ground reflected fields down in intensity. From loop current and physical dimensions and the oscillator-receiver spacing the resultant field is calculated and compared with the field to be measured.

3. Modified short-wave method. This is the method we have chiefly used and which appears at the moment to be most promising. From a knowledge of the impedances of antenna and receiver input circuits, the voltage transfer ratio from effective antenna input to resultant grid input can be calculated for optimum power transfer conditions, and to a good degree of accuracy. This factor, together with the antenna effective height and overall set gain, permits a measurement of the field intensity. In effect this is a variation of the Friis and Bruce method.